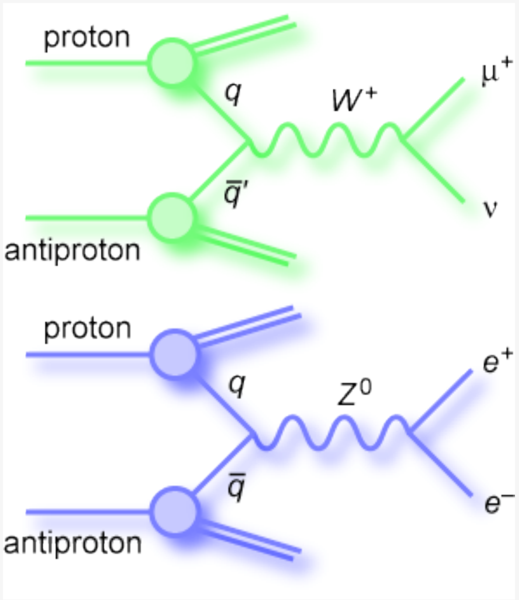
Electroweak Measurements from the Tevatron



La Thuile 2009

Eva Halkiadakis
Rutgers University

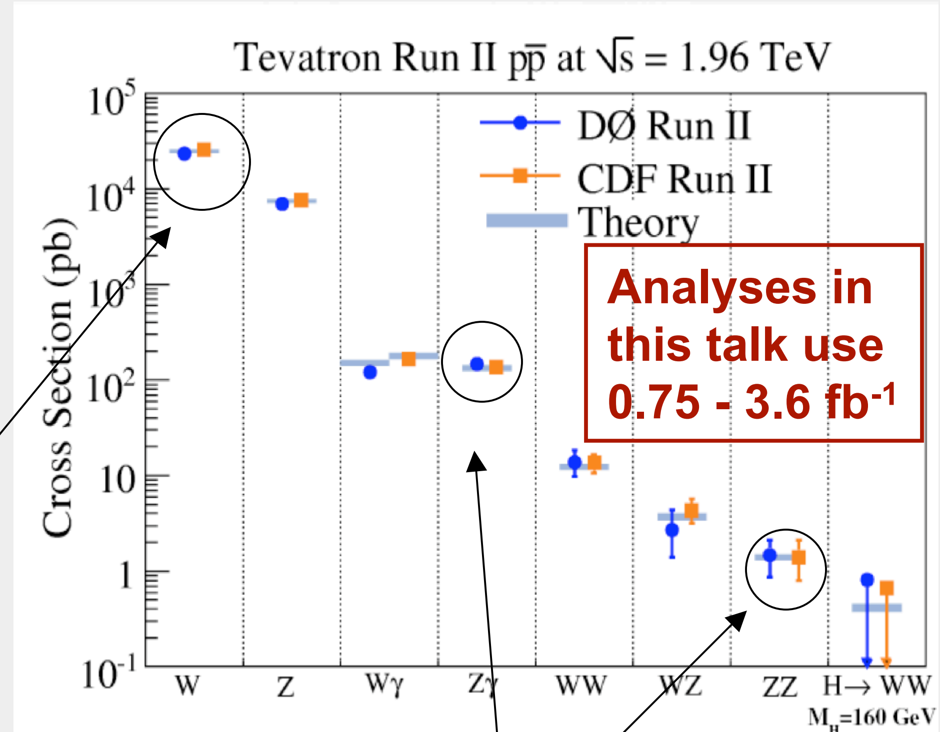
For the CDF and DØ Collaborations

W & Z Bosons

- EWK measurements provide:
  - high precision tests of the SM
  - indirect knowledge about the Higgs boson or possible new physics
- **Tevatron is a Vector Boson factory!**

Events produced in ~1fb^{-1} : (ℓ = e, μ)

≈ 5,000,000	$W \to \ell\nu$
≈ 500,000	$Z \to \ell\ell$
≈ 32,000	$W\gamma \to \ell\nu\gamma$
≈ 8000	$Z\gamma \to \ell\ell\gamma$
≈ 4000	$WW/WZ \to \ell\nu jj$
≈ 600	$WW \to \ell\nu\ell\nu$
≈ 50	$WZ \to \ell\nu\ell\ell$
≈ 40	$ZZ \to \ell\ell\nu\nu$
≈ 6	$ZZ \to \ell\ell\ell\ell$



Analyses in this talk use 0.75 - 3.6 fb^{-1}

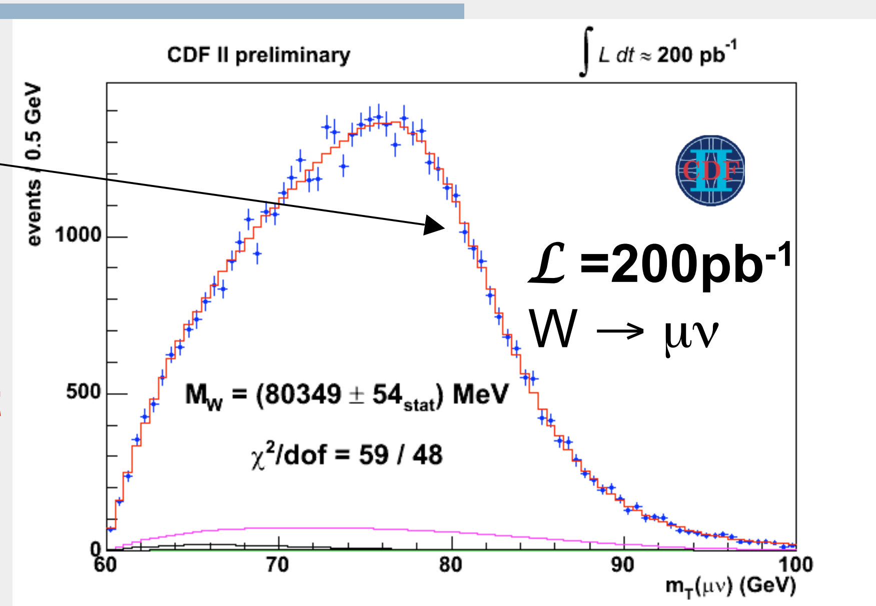
- Single Boson Production
  - Precision measurement W mass
    - Higgs mass constraint
  - W production cross section asymmetry
    - Parton distributions inside proton
- Diboson Production
  - Zγ production
    - First measurement of $Z\gamma \to \nu\nu\gamma$ final state at Tevatron
  - Observation of ZZ
  - Limits on *anomalous* trilinear gauge couplings

W Mass

PRL 99, 151801 (2007).
PRD 77, 112001 (2008).

- W mass information contained in location of Jacobian edge in m_T
- Fit to transverse mass, momentum and missing energy distributions in e and μ channels and combine
- **CDF 200pb^{-1} result is the world's most precise single measurement**

  $m_W = 80413 \pm 34_{stat} \pm 34_{syst}$ MeV
- Total uncertainty 48 MeV
- Uncertainty on world average reduced ~15% (29 to 25 MeV)



Large statistical component
Scale partially with statistics
External input → new PDF fits

Improvement in PDF uncertainties will reduce total error on W mass → e.g. W charge asymmetry measurement

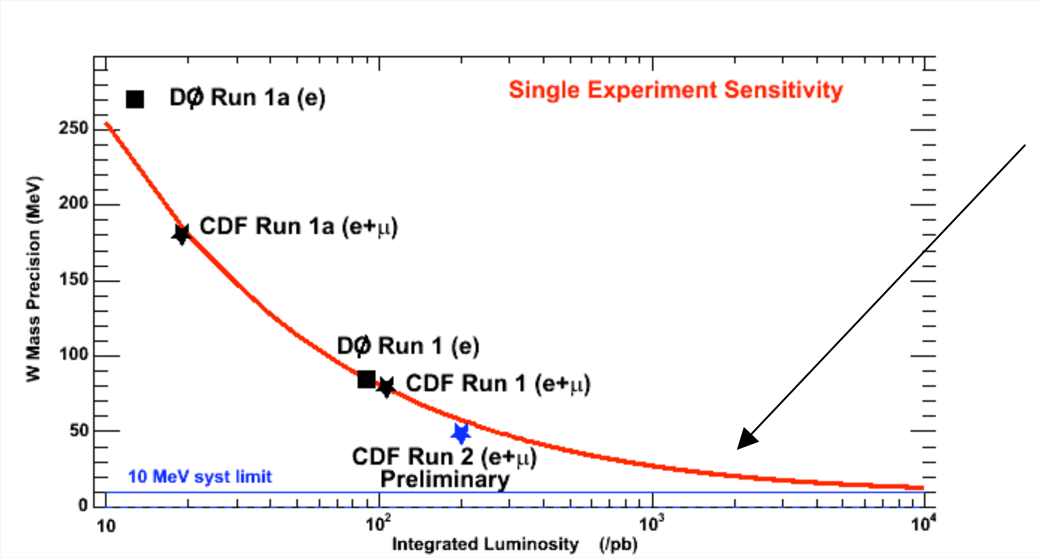
Syst. + Stat. uncertainties (m_T)

CDF II preliminary — L = 200 pb^{-1}

m_T Uncertainty [MeV]	Electrons	Muons	Common
Lepton Scale	30	17	17
Lepton Resolution	9	3	0
Recoil Scale	9	9	9
Recoil Resolution	7	7	7
$u_{\parallel}$ Efficiency	3	1	0
Lepton Removal	8	5	5
Backgrounds	8	9	0
$p_T(W)$	3	3	3
PDF	11	11	11
QED	11	12	11
Total Systematic	39	27	26
Statistical	48	54	0
Total	62	60	26

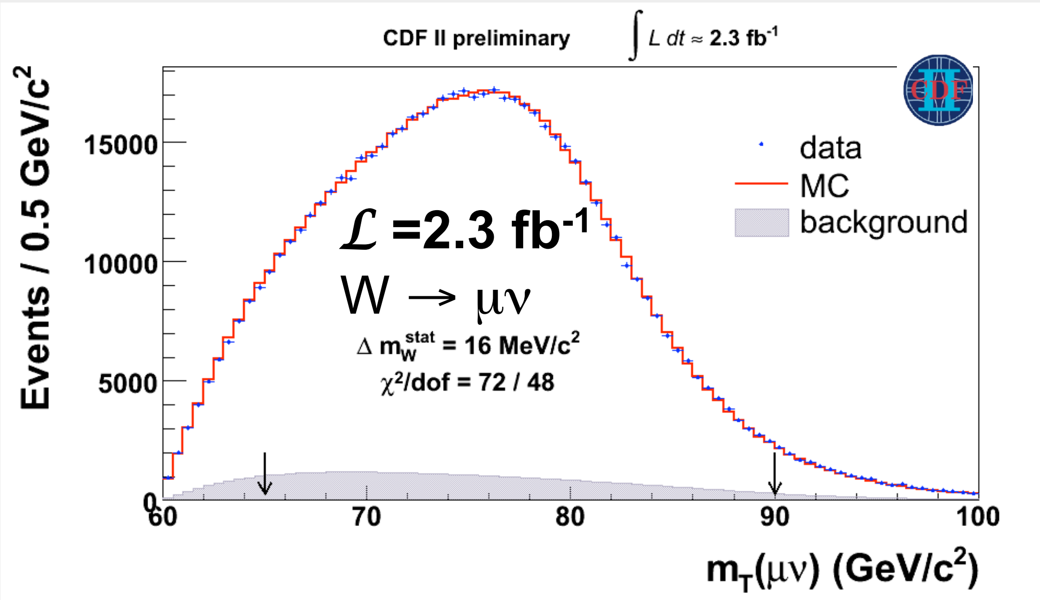
W Mass Projections

Projection from previous Tevatron measurements



Expect ΔM_W < 25 MeV with ~2 fb^{-1} collected and being analysed

Studies in progress confirm that most systematics scale with luminosity as expected



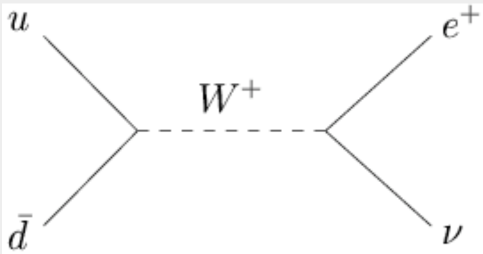
Expected statistical uncertainties

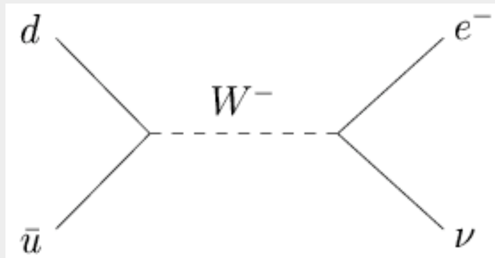
$W \rightarrow \mu\nu$	Δm_W^{stat}
published (200pb^{-1})	54 MeV/c^2
expected (2.3fb^{-1})	16 MeV/c^2
fit (2.3fb^{-1})	16 MeV/c^2

$W \rightarrow e\nu$	Δm_W^{stat}
published (200pb^{-1})	48 MeV/c^2
expected (2.4fb^{-1})	14 MeV/c^2
fit (2.4fb^{-1})	15 MeV/c^2

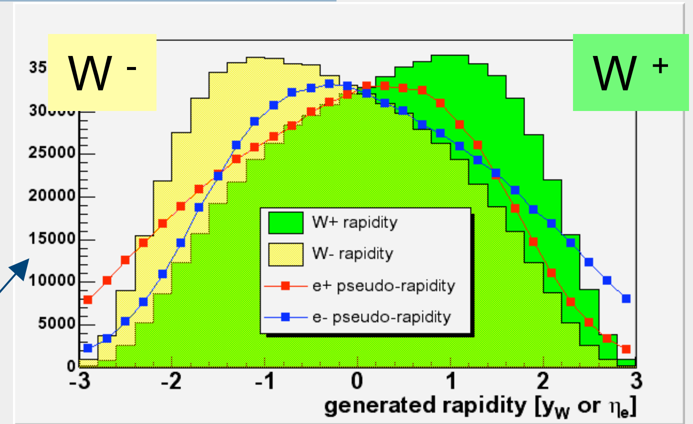
W Production Charge Asymmetry

At the Tevatron, $W^{\pm}$ are produced primarily by:





u quark carries higher fraction of p momentum!

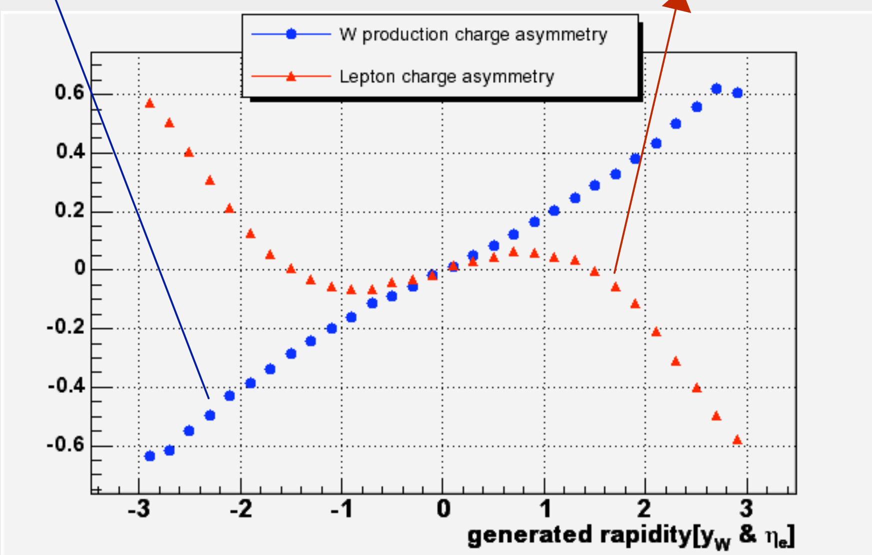


←anti-proton direction proton direction→

W Charge Asymmetry:

$$A(y_W) = \frac{d\sigma_+/dy_W - d\sigma_-/dy_W}{d\sigma_+/dy_W + d\sigma_-/dy_W}$$

$$A_l(\eta) = \frac{d\sigma(l^+)/d\eta - d\sigma(l^-)/d\eta}{d\sigma(l^+)/d\eta + d\sigma(l^-)/d\eta}$$



Measurement of the W charge asymmetry constrains PDF's of the proton! (sensitive to d(x)/u(x) ratio)

Lepton charge asymmetry is a convolution of both the *W* charge asymmetry and V-A *W* decay structure

- Results in "turn-over" at high |η|
- W^+'s produced boosted in proton direction and polarized in the antiproton direction

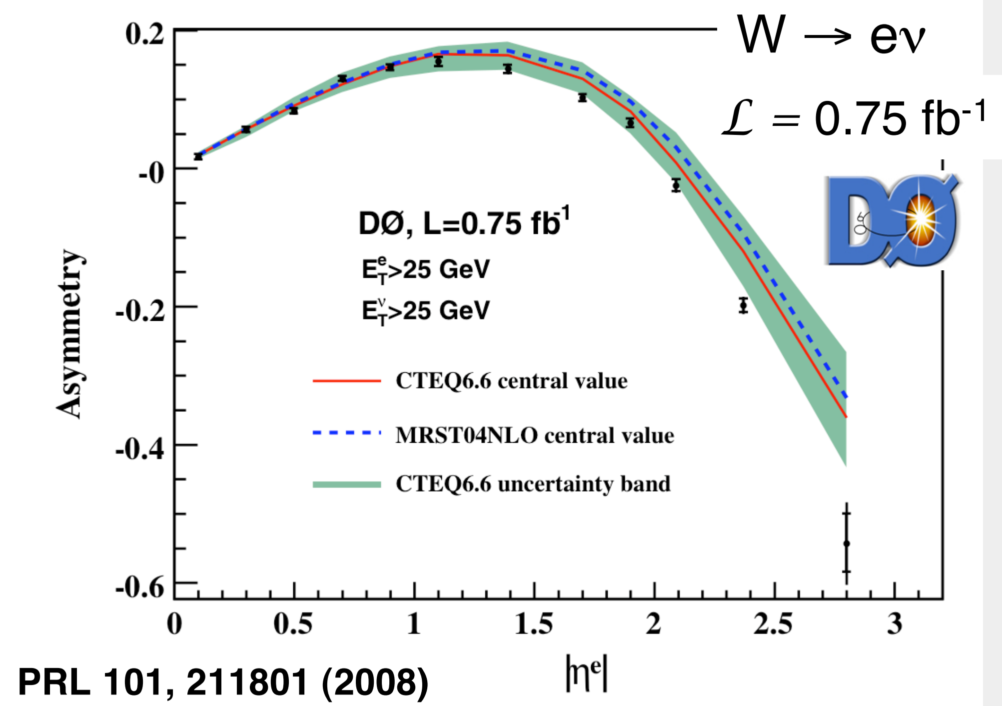
W charge asymmetry does not suffer from "turn-over" effect

Lepton Charge Asymmetry

- Traditionally we measure lepton charge asymmetry
  - leptonic W decay involves $\nu \rightarrow P_z^{\nu}$ is unmeasured
  - Difficult to measure W rapidity directly

$$A_l(\eta) = \frac{d\sigma(l^+)/d\eta - d\sigma(l^-)/d\eta}{d\sigma(l^+)/d\eta + d\sigma(l^-)/d\eta}$$

- Charge identification is crucial for this measurement.
  - Measure charge fake rate using $Z \rightarrow e^+e^-$ data sample.
  - Charge misidentification rate ranges from 0.2% in central region to 0.9% in forward region (with absolute uncertainty from 0.1% - 2.6% depending on η)



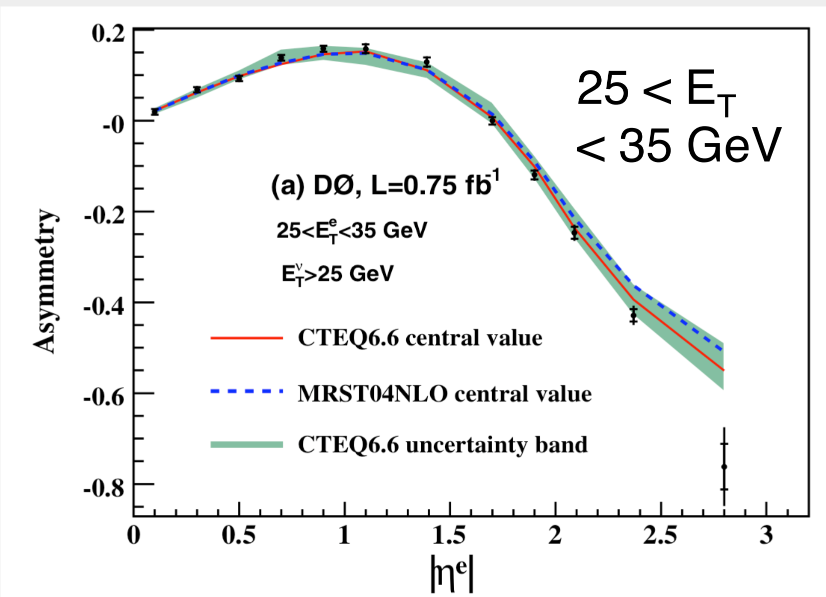
PRL 101, 211801 (2008)

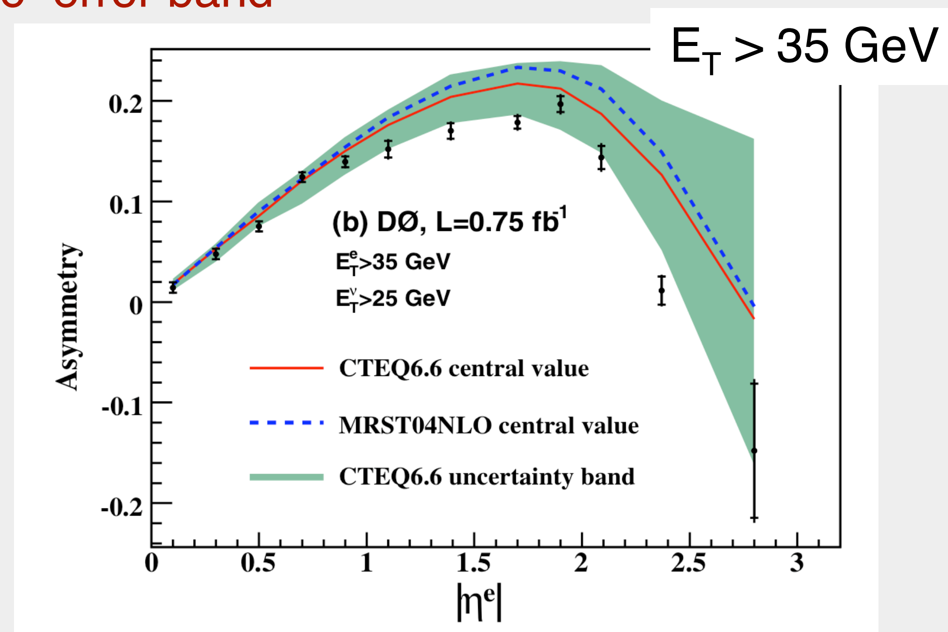
The measured charge asymmetry tends to be lower than the theoretical predictions for high $|\eta_e|$.

CTEQ6 NLO:P. M. Nadolsky et al., Phys. Rev. D 78, 013004 (2008). CTEQ6 error PDFs: D. Stump et al., J. High Energy Phys. 10 (2003) 046. MRST06NLO: A. D. Martin, R. G. Roberts, W. J. Stirling, and R. S. Thorne, Phys. Lett. B 604, 61 (2004).

Lepton Charge Asymmetry

- Also measure the asymmetry in two bins of electron E_T
  - $25 < E_T < 35$ GeV and $E_T > 35$ GeV
- For a given η_e, the two E_T regions probe different ranges of y_W
  - Allow a finer probe of the x dependence
  - For higher E_T, electron direction closer to W direction
  - Improve sensitivity to the PDFs
- Agreement in the low E_T bin much better than in the high E_T bin
  - Comparisons with CDF ongoing
- Precision better than current CTEQ6.6 error band

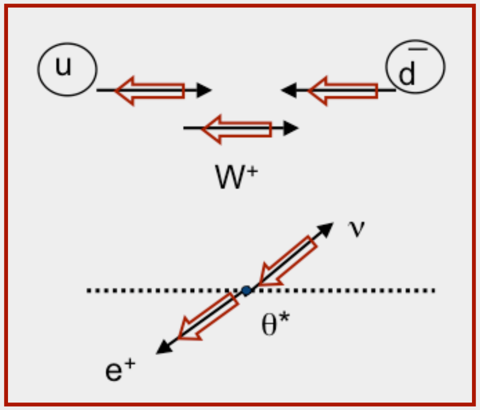




PRL 101, 211801 (2008)

W Charge Asymmetry

$$A(y_W) = \frac{d\sigma_+/dy_W - d\sigma_-/dy_W}{d\sigma_+/dy_W + d\sigma_-/dy_W}$$



How to reconstruct y_W?

$$y_W = \frac{1}{2}\ln\left(\frac{E - P_z}{E + P_z}\right) \qquad \vec{P_z^W} = \vec{P_z^l} + \vec{P_z^\nu}$$

can't measure !!!

New technique by CDF:

$$M_W^2 = (E_l + E_\nu)^2 - (\vec{P_l} + \vec{P_\nu})^2$$

- Use W mass constraint to reconstruct neutrino P_z
  - Two possible y_W solutions
- Each solution receives a weight probability according to:
  - V-A decay structure
    - Depends on p_T^W, y_W, θ^* (lepton angle in W rest frame)
  - W differential cross-section: $\sigma(y_W)$
- Iterate, since $\sigma(y_W)$ depends on $A(y_W)$

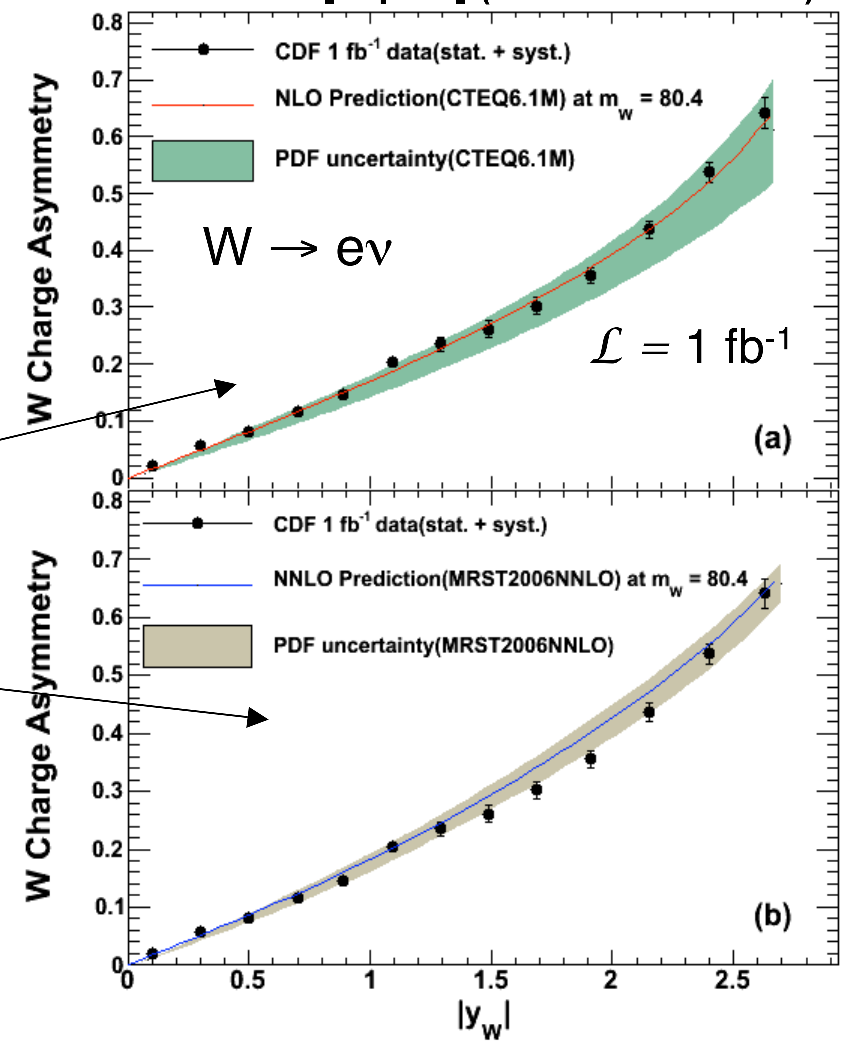
Method documented in PRD 77, 111301(R) (2008)

First Direct Measurement of $A(y_W)$

- **First direct measurement of *W* charge asymmetry**
  - Despite additional complication of multiple solutions, it works!
  - Systematics <1.5 % for $|y_W| > 2.0$
  - Appears that it will have impact on *d/u* of proton
- Compare to CTEQ6M (NLO) and MRST2006 (NNLO) PDFs and their uncertainties
- **Both experiments working with PDF fitting groups to incorporate results**

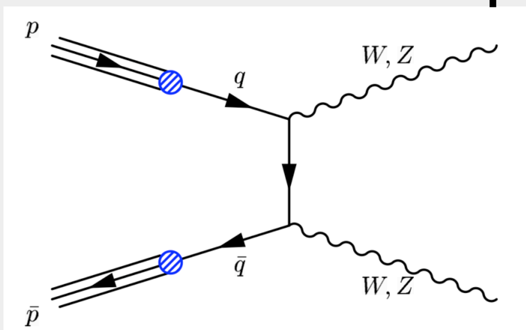
NNLO Prediction: C. Anastasiou et al., Phys. Rev. D69 , 094008 (2004)
MRST 2006 PDFs: A. D. Martin et al., hep-ph/0706.0459, Eur. Phys. J., C28 , 455 (2003)
CTEQ6M PDFs: J. Pumplin et al., hep-ph/0201195

arXiv:0901.2169 [hep-ex] (Submitted to PRL)

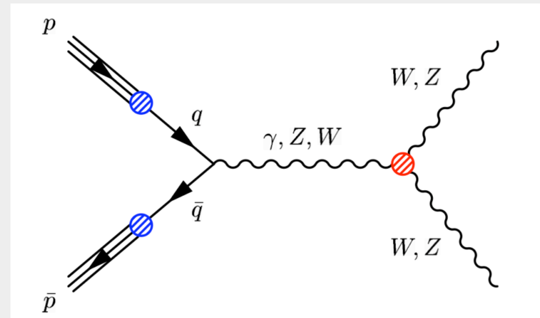


Diboson Production

t-channel: Fermion-Boson Couplings

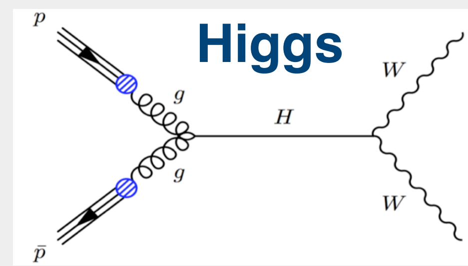


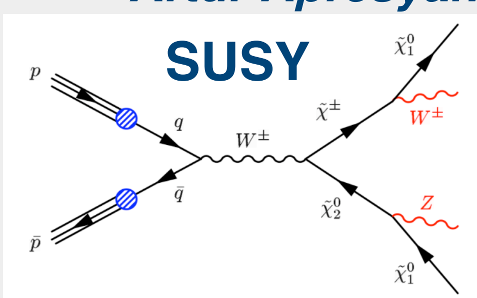
s-channel: Boson-Boson Couplings

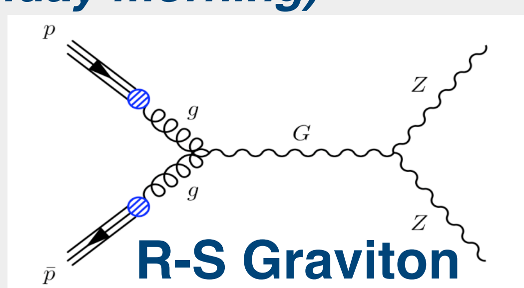


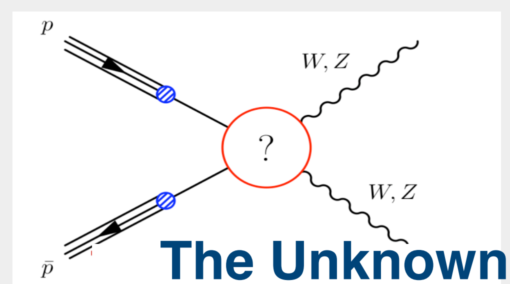
<u>**Why study diboson Production?**</u>

- Relationships between the masses and couplings of the *W* and *Z*
- Sensitive to new physics in TGC (trilinear gauge couplings)
  - Tevatron complementary to LEP
  - Explores higher center-of-mass energy than LEP
  - Different combinations of couplings
- Backgrounds to “new physics”: Higgs, top, SUSY …
  - ***See “Low Mass SM Higgs at Tevatron” talk by Artur Apresyan (Friday morning)***



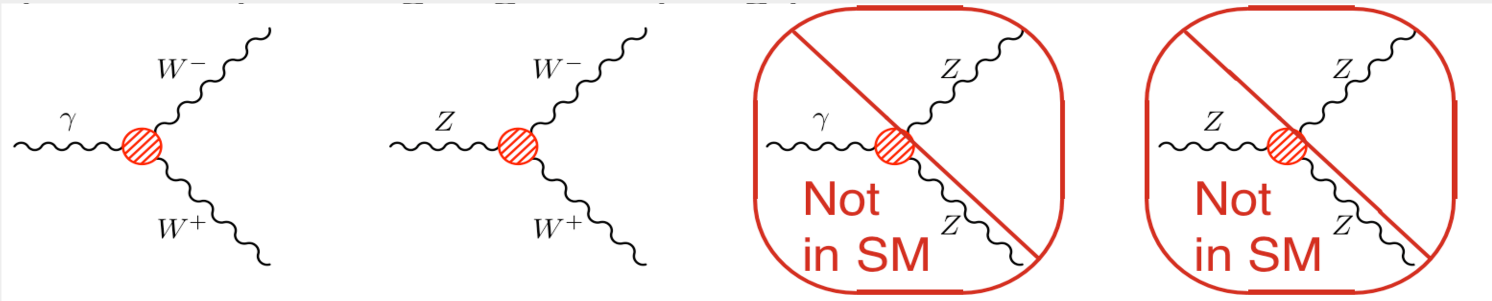






Neutral Triple Gauge Couplings

Boson-Boson Couplings:

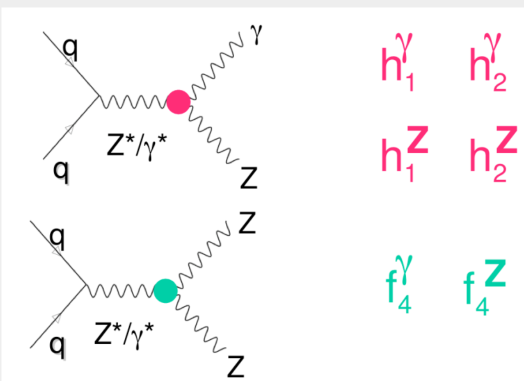


Not permitted in SM:
ZZγ, Zγγ, ZZZ

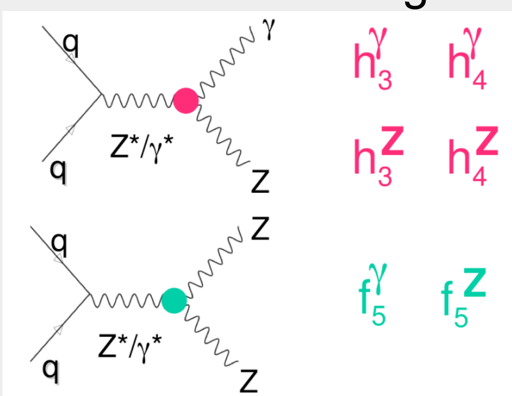
I will focus on this today

Describe these anomalous couplings in terms of CP violating and CP conserving parameters. Usually described by a form factor to ensure unitarity, assuming a value of Λ **(energy scale for new physics)**.

CP violating

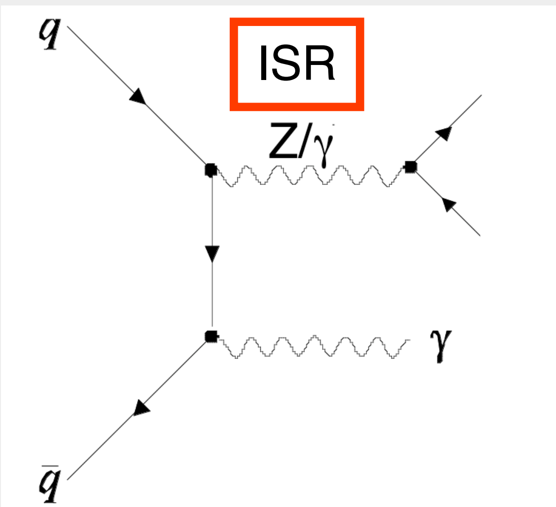


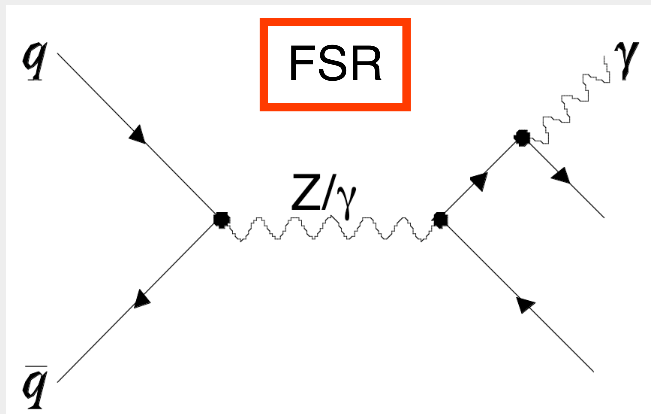
CP conserving

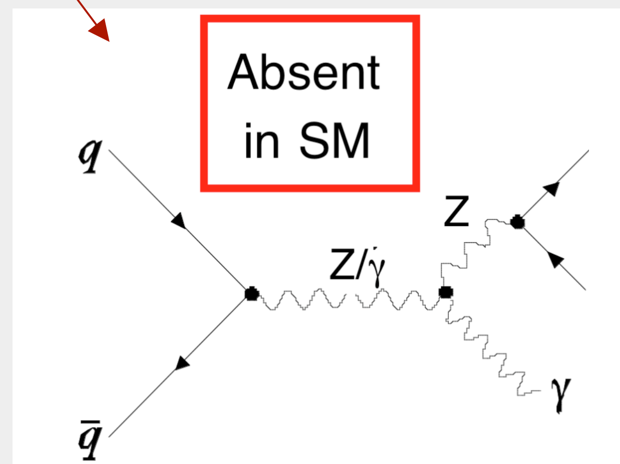


Zγ Production

- SM predicts two tree-level diagrams via ISR and FSR radiation
- Zγγ and ZZγ couplings vanish at tree-level in the SM







- eeγ and μμγ channels extensively studied at Tevatron
- **Today: first measurement of Zγ→ννγ final state at Tevatron**
  - **Very challenging**
  - **Higher acceptance**
  - **Higher BR to νν than to ℓℓ**
  - **No FSR in ννγ final state**

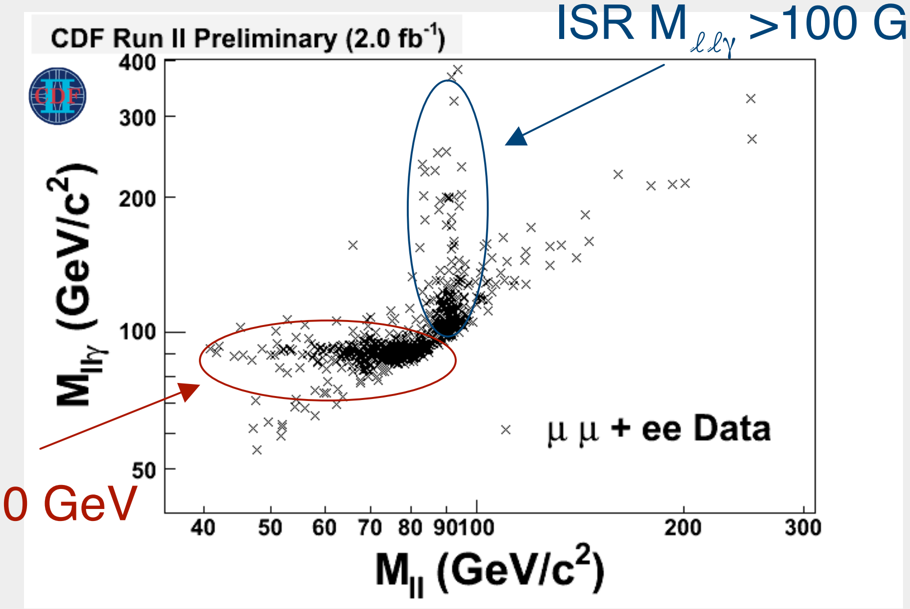
$Z\gamma \rightarrow \ell\ell\gamma$

- Two isolated high p_T leptons
- A photon with $E_T\gamma$ > 7 GeV
- $M_{\ell\ell}$ > 40 GeV (CDF)
- $M_{\ell\ell}$ > 30 GeV (DØ)
- $\Delta R_{\ell\gamma}$ > 0.7

Backgrounds:
Z+jets, γ+jets

FSR
$M_{\ell\ell\gamma}$ <100 GeV

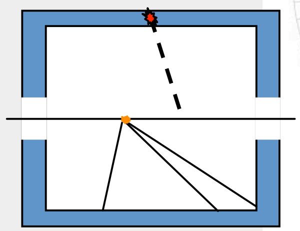
ISR $M_{\ell\ell\gamma}$ >100 GeV

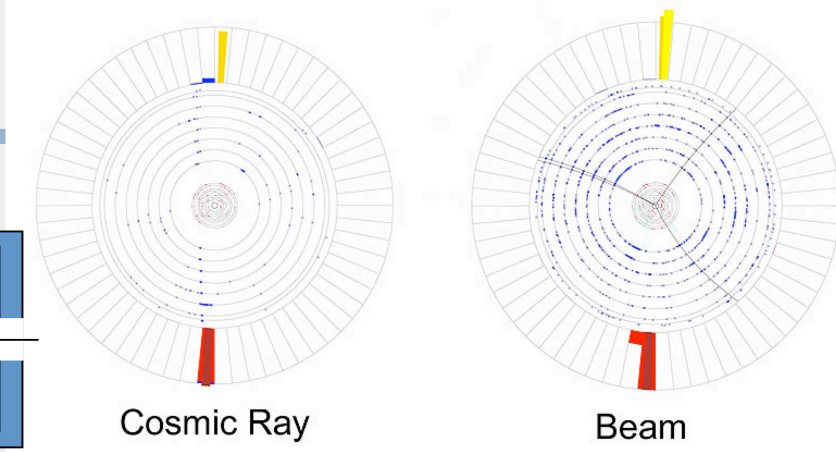


Experiment	Luminosity	#events eeγ ($\mu\mu\gamma$)	Measured σ xBR (pb)	NLO Prediction (pb)
DØ [PLB 653, 378 (2007)]	1.1 fb-1	453 (515)	4.96 ± 0.30 (stat.+syst.) ± 0.30 (lumi.)	4.7 ± 0.2
CDF (ISR)	1.1 fb-1 (ee) 2.0 fb-1($\mu\mu$)	154 (119)	1.2 ± 0.1(*stat.*) ± 0.2(*syst.*) ± 0.1(*lumi.*)	1.2 ± 0.1pb
CDF (FSR)	1.1 fb-1 (ee) 2.0 fb-1($\mu\mu$)	236 (269)	3.4 ± 0.2(*stat.*) ± 0.2(*syst.*) ± 0.2(*lumi.*)	3.3 ± 0.3pb

$Z\gamma \rightarrow \nu\nu\gamma$

- $\mathcal{L}$ = 3.6 fb^{-1}
- $E_T\gamma$ > 90 GeV
- MET > 70 GeV
- No jets with E_T>15GeV
- No high p_T tracks
- require $|z_{EM} - z_V| < 10$ cm
  - Removes cosmic or halo muon brem
  - Z_{EM} assumes EM shower initiated by photons pointing back to z axis
  - Z_V reconstructed event vertex





Beam and cosmic ray initiated events can be distinguished by the signature seen in the tracking system. In a cosmic ray event, a single vertical track (as evidenced by the blue dots) indicates the passage of a single cosmic ray muon.

	Number of events
$W \rightarrow e\nu$	9.67 ± 0.30 (stat.) ± 0.48 (syst.)
$non-collision$	5.33 ± 0.39 (stat.) ± 1.91 (syst.)
$W/Z + jet$	1.37 ± 0.26 (stat.) ± 0.91 (syst.)
$W\gamma$	0.90 ± 0.07 (stat.) ± 0.12 (syst.)
Total background	17.3 ± 0.6 (stat.) ± 2.3
$N_{\nu\nu\gamma}^{SM}$	33.7 ± 3.4
N_{obs}	51

$\sigma \times Br(Z \rightarrow \nu\nu)$ =
32 ± 9 (stat+syst) ± 2 (lumi) fb

5.1σ significance
First observation of $Z\gamma \rightarrow \nu\nu\gamma$ at Tevatron!

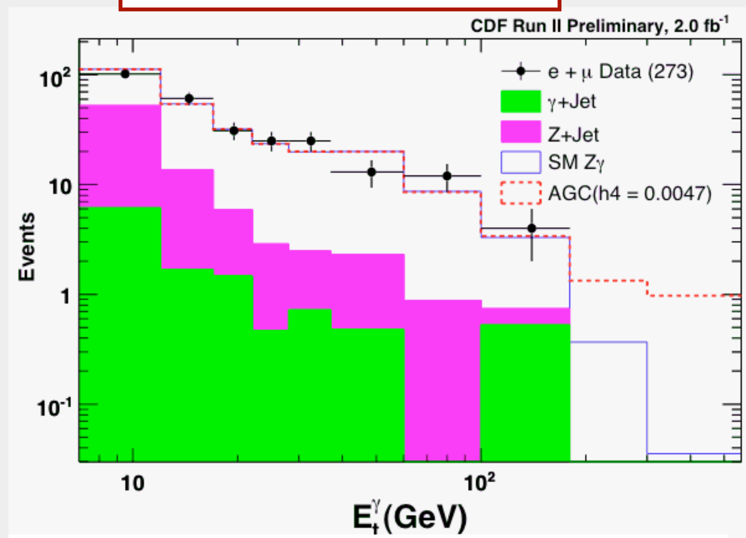
In agreement with NLO prediction:
39 ± 4 fb

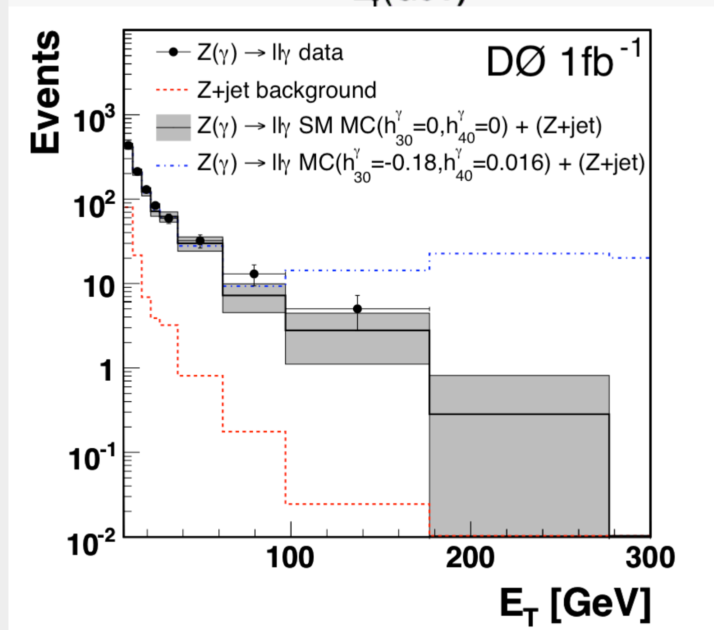
Submitted to PRL
arXiv.org:0902.2157

Zγ Anomalous Couplings

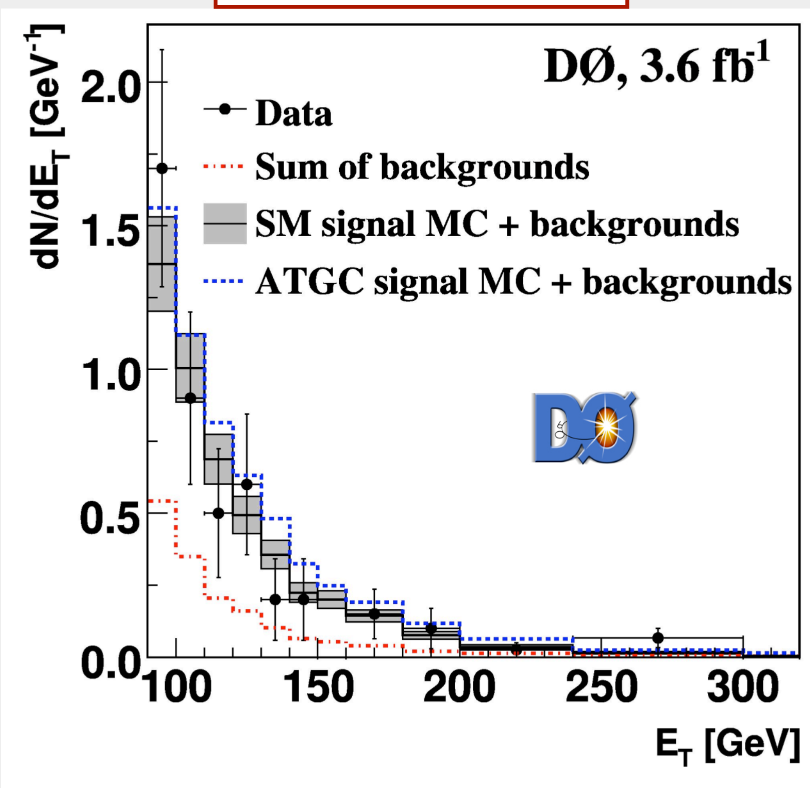
- Data are consistent with the SM prediction
- Use photon E_T spectrum to set limits on anomalous ZZγ, Zγγ couplings

Zγ→ℓℓγ Channels





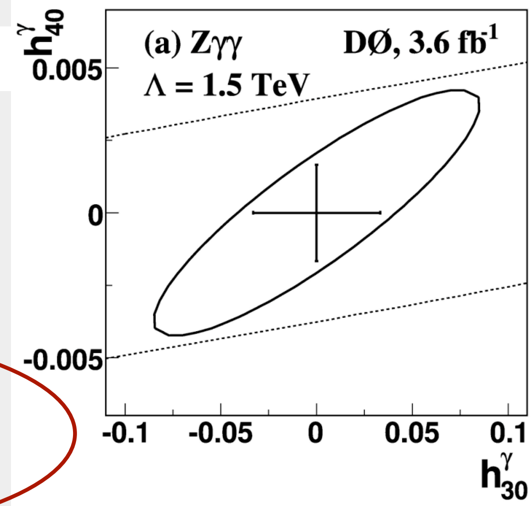
Zγ→ννγ Channel



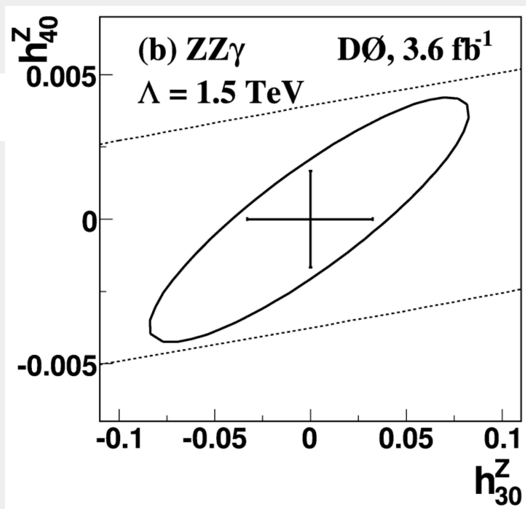
Zγ Anomalous Couplings

95%CL on CP conserving parameters

DØ	Λ = 1.2 TeV	Λ = 1.5 TeV
$Z\gamma \to \ell\ell\gamma$ 1 fb^{-1}	$|h_3^\gamma|<0.085$ $|h_4^\gamma|<0.0054$	$|h_3^\gamma|<0.079$ $|h_4^\gamma|<0.0036$
	$|h_3^Z|<0.083$ $|h_4^Z|<0.0054$	$|h_3^Z|<0.075$ $|h_4^Z|<0.0037$
$Z\gamma \to \nu\nu\gamma$ 3.6 fb^{-1}	$|h_3^\gamma|<0.042$ $|h_4^\gamma|<0.0029$	$|h_3^\gamma|<0.037$ $|h_4^\gamma|<0.0020$
	$|h_3^Z|<0.041$ $|h_4^Z|<0.0029$	$|h_3^Z|<0.036$ $|h_{40}^Z|<0.0020$
Zγ combination	$|h_3^\gamma|<0.038$ $|h_4^\gamma|<0.0025$	$|h_3^\gamma|<0.033$ $|h_4^\gamma|<0.0017$
	$|h_3^Z|<0.037$ $|h_4^Z|<0.0025$	$|h_3^Z|<0.033$ $|h_4^Z|<0.0017$
CDF	**Λ = 1.2 TeV**	
$Z\gamma \to \ell\ell\gamma$ 1–2 fb^{-1}	$|h_3^\gamma|<0.084$ $|h_4^\gamma|<0.0047$	
	$|h_3^Z|<0.083$ $|h_4^Z|<0.0047$	
LEP		
	$-0.049<h_3^\gamma<0.008$ $-0.002<h_4^\gamma<0.034$	
	$-0.20<h_3^Z<0.07$ $-0.05<h_4^Z<0.12$	

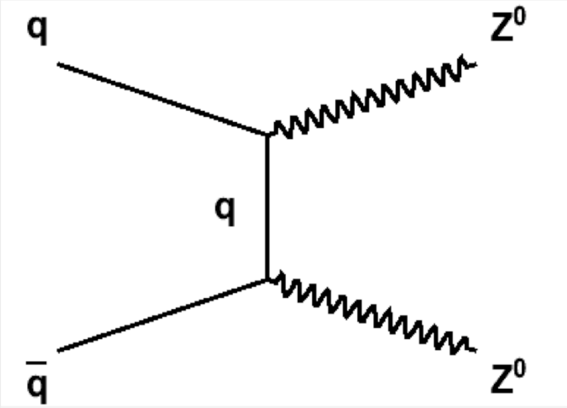


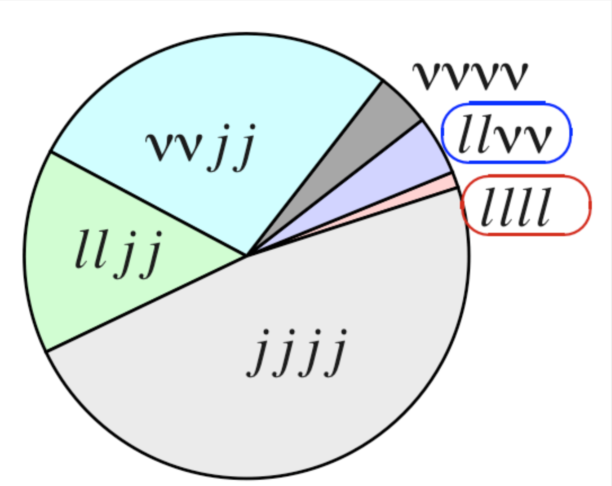
Best limits from Tevatron so far



LEP does not scale couplings with the form-factor, which makes direct comparison more complex

ZZ Production





- Very small cross-section
  - NLO cross section: 1.4 ± 0.1 pb
    Campbell, Ellis, PRD 60 (1999) 113006
- Two viable modes (assume e and μ leptons):
  - $\ell\ell\ell\ell$: ~0.5%
    - Small branching ratio
    - Clean Sample
  - $\ell\ell\nu\nu$: ~3.0%
    - 6 times large branching ratio
    - Large Backgrounds (*WW* ,*WZ* ,Drell-Yan)
- Strategy: both DØ and CDF consider and combine both decay modes

ZZ Production

First measurement!

$\mathcal{L}$ =1.9fb^{-1} **PRL100, 201801 (2008)**

Observation!

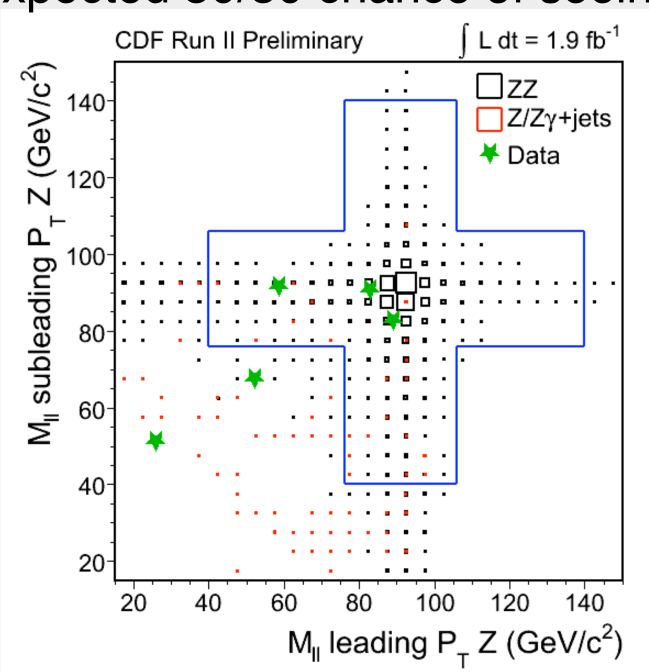
$\mathcal{L}$ =2.7fb^{-1} **PRL 101, 171803 (2008)**

Observed results

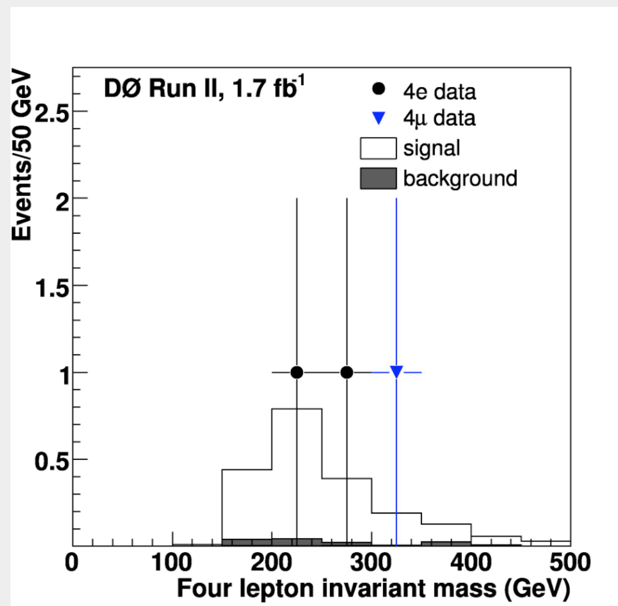
Channel	$\ell\ell\nu\nu$	$\ell\ell\ell\ell$	Combined
P-value	0.12	1.1×10^{-5}	5.1×10^{-6}
Significance	1.2σ	4.2σ	4.4σ

Expected 50/50 chance of seeing 5σ

Channel	$\ell\ell\nu\nu$ (2.7fb^{-1})	$\ell\ell\ell\ell$ (1.7fb^{-1})	Combined (also with 1fb^{-1} 4ℓ measurement)
P-value	0.42×10^{-2}	4.3×10^{-8}	6.2×10^{-9}
Significance (expected)	2.6σ (2.0σ)	5.3σ (3.7σ)	5.7σ (5.2σ)



P-value: Probability for data to be described by background-only hypothesis

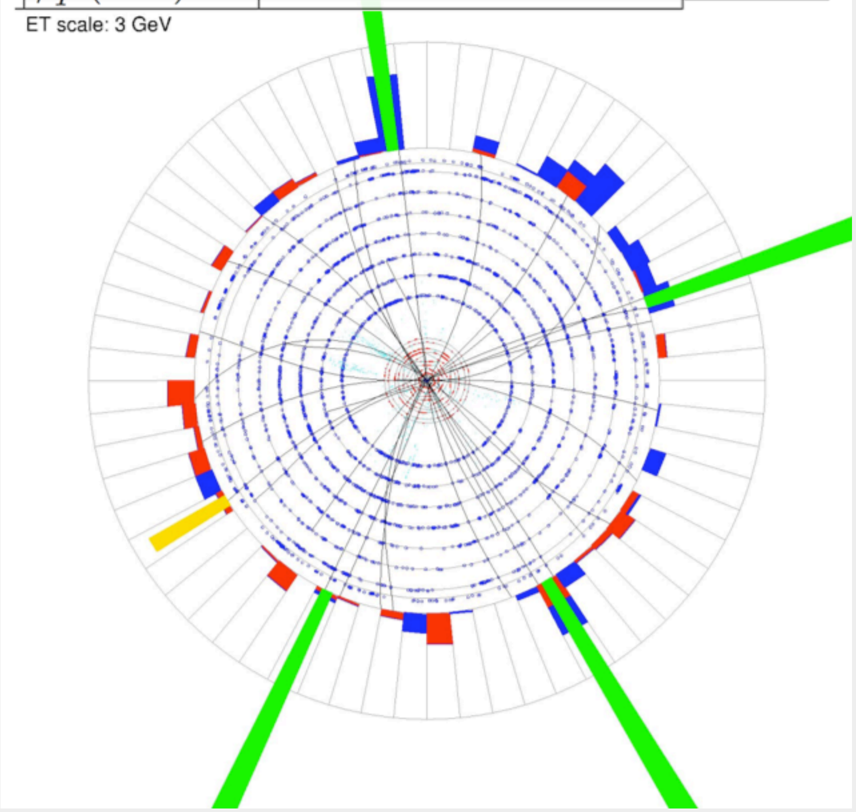


$$\sigma(ZZ) = 1.4\ ^{+0.7}_{-0.6}\,\text{pb}$$

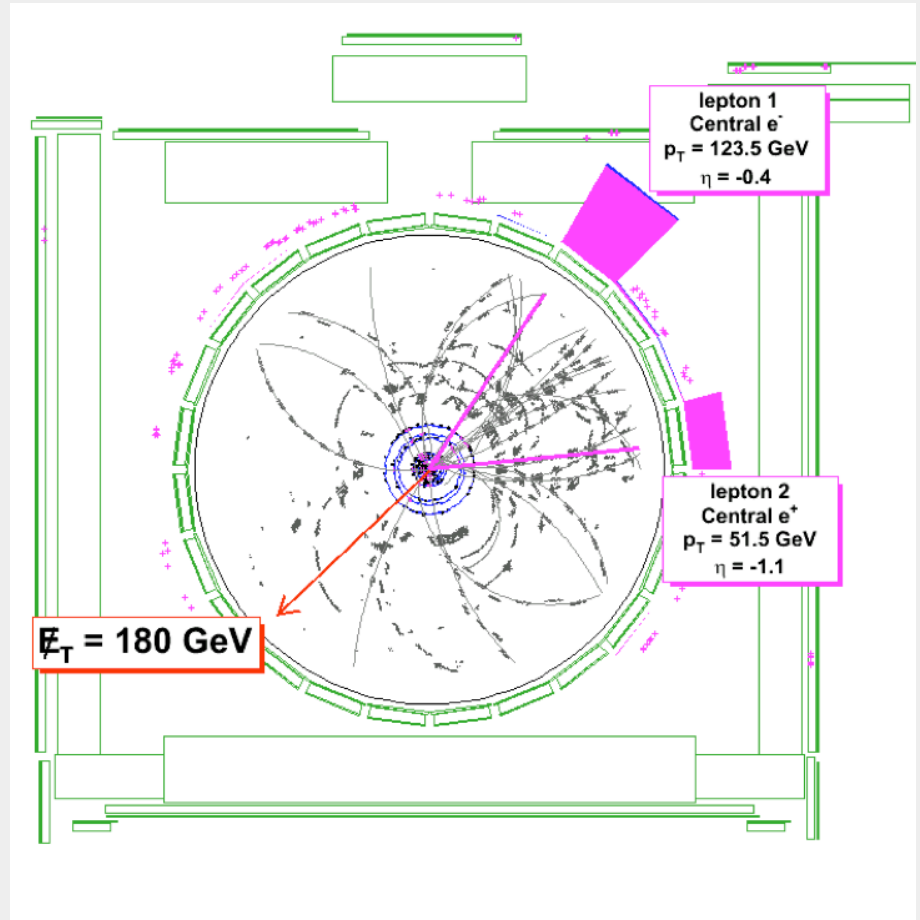
$$\sigma(ZZ) = 1.60\ \pm 0.65\,\text{pb}$$

ZZ Candidates

	μ_1^+	μ_2^-	μ_3^-	μ_4^+
p_T (GeV)	115.5	77.5	42.1	24.0
η_D	0.02	-0.98	0.80	-1.89
	$\mu_1^+\mu_3^-$		$\mu_2^-\mu_4^+$	
dimass (GeV)	147.6		89.8	
$Z\ p_T$ (GeV)	79.9		62.4	
$\not\!\!E_T$ (GeV)		2.8		

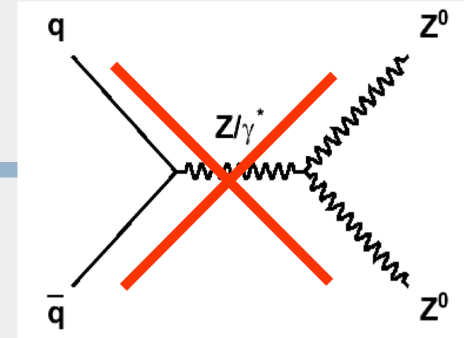


4μ event



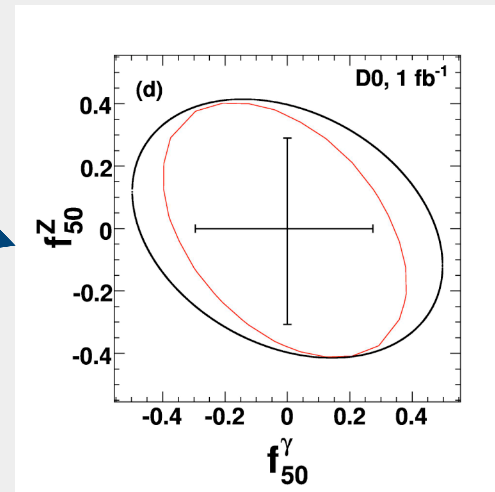
eeνν event

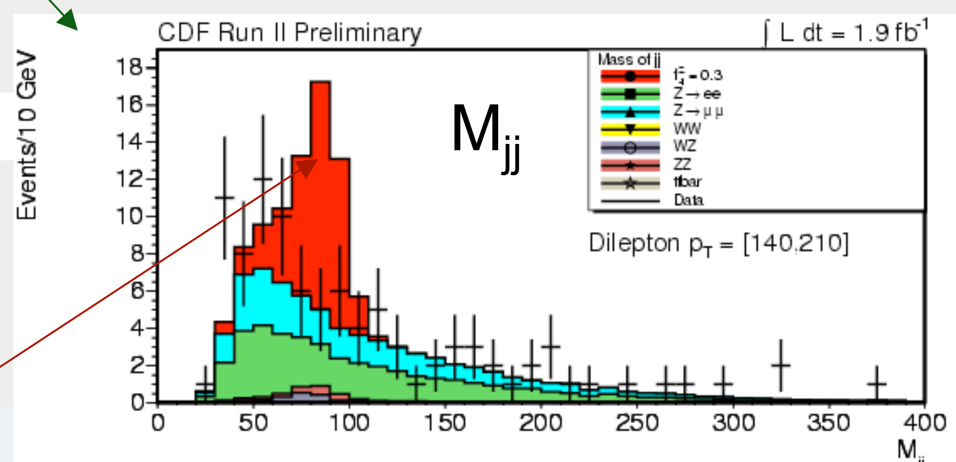
ZZ Anomalous Couplings



<u>95%CL on CP violating and conserving parameters</u>

DØ	**Λ = 1.2 TeV**
$ZZ \to \ell\ell\ell\ell$ 1 fb^{-1}	$\lvert f_4^{\gamma}\rvert<0.26$ $-0.30<\lvert f_5^{\gamma}\rvert<0.28$ $\lvert f_4^{Z}\rvert<0.28$ $-0.31< \lvert f_5^{Z}\rvert<0.29$
CDF	**Λ = 1.2 TeV**
$ZZ \to \ell\ell jj$ 1.9 fb^{-1} Use dijet mass spectrum in high $p_T(Z)$ region	$\lvert f_4^{\gamma}\rvert<0.10$ $\lvert f_5^{\gamma}\rvert<0.11$ $\lvert f_4^{Z}\rvert<0.12$ $-0.13<\lvert f_5^{Z}\rvert<0.12$
LEP	
	$-0.17<f_4^{\gamma}<0.19$ $-0.32<f_5^{\gamma}<0.36$ $-0.30<f_4^{Z}<0.30$ $-0.34<f_5^{Z}<0.38$





Expected AGC signal from f_4^Z =0.3 (LEP Limit)

Conclusions

- Currently, CDF measurement of the W boson mass gives the single most precise for one experiment
  - Upcoming precision W mass measurements will further test the SM and provide new indirect limits on Higgs mass
- New precision measurements of the W charge asymmetry testing accuracy of our knowledge of the proton structure

- Measuring processes with cross sections similar to Higgs!
  - First observation of $Z\gamma \rightarrow \nu\nu\gamma$ at Tevatron!
  - ZZ production has been observed at the Tevatron!
  - New limits set on anomalous couplings for ZZZ / $ZZ\gamma$ / $Z\gamma\gamma$ production
  - We are now measuring diboson production and couplings with greater and greater precision

CDF: http://www-cdf.fnal.gov/physics/physics.html
DØ: http://www- d0.fnal.gov/Run2Physics/WWW/results.htm